

**STUDIES OF HIGH ENERGY
HADRON-HADRON REACTIONS**

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Studies of High Energy

Hadron-Hadron Reactions

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Abstract

The first part of this thesis concerns the possibility of obtaining a quantity that reveals more of the primary scattering of partons, than the single particle spectra for high- p_T reactions. K^-K^- is shown to be such a quantity for 90° scattering. A p_T -dependence of -5.4 is found from data from FNAL and ISR. A model for low- p_T baryon P_T production is presented. This one-dimensional string model gives longitudinal single particle spectra in good agreement with exp. data. A model for polarization of inclusively produced hyperons is presented. A baryon is pictured as a Y-shaped string with quarks at the ends. One of the quarks is kicked out in the reaction, leading to a basically one-dim. string system. The motion of the string junction is shown to be important for the understanding of polarization phenomena. Lowest order QCD is studied with respect to color factors in the production amplitude in order to find final string configurations in high- p_T events. The basis for a Monte Carlo program for complete high- p_T events is discussed.

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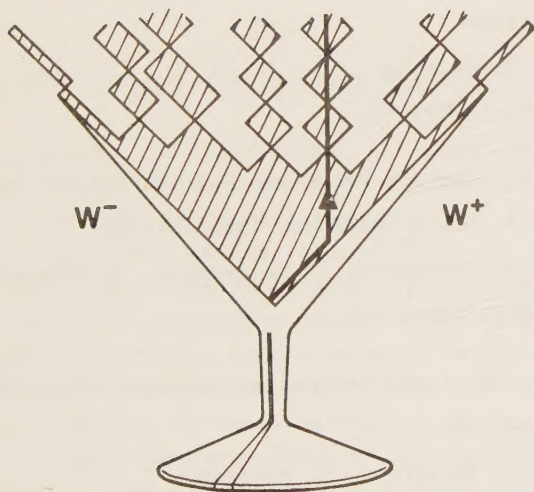
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IT'S STRINGTIME FOR PHYSICS



HOW TO MAKE A HADRON COCKTAIL MIXED
ACCORDING TO THE RECIPE OF THE LUND MODEL
BASED ON THE RELATIVISTIC MASSLESS STRING

This thesis is based on the following papers:

- I Production of K^+ and K^- as a Test on Models for Large p_T
Hadronic Reactions
G. Gustafson, O. Månsson
Phys. Lett. 81B (1979) 75

- II A Model for the Reaction Mechanism and the Baryon Fragmentation
Distributions in Low p_T Hadronic Interactions
B. Andersson, G. Gustafson, I. Holgersson, O. Månsson
Nucl. Phys. B178 (1981) 242

- III Hyperon Polarization and Transverse Momentum Properties in
Proton Fragmentation
B. Andersson, G. Gustafson, O. Månsson
LUTP 82-13 November 1982

- IV Fragmentation Structure in High- p_T Events
H.-U. Bengtsson, O. Månsson
LUTP 82-14 November 1982

1. Introduction

Hadrons are particles that can participate in strong interactions. Although two of them, the proton and the neutron, as the buildingblocks of the nucleus provide the basis for the atom, not much of their properties are observed in everyday life. It is the electron shells, whose structure is determined by electro-magnetic interactions, that is responsible for the great diversity in shape and colour around us. However, the hadrons will turn out to be quite colourful in another way. But first, let us return to the one thing common for the hadrons, the strong interaction.

2. The Strong Interaction (A Brief History)

From experiments on scattering of α -particles of atoms, Rutherford in 1911 concluded that all the positive charge and nearly all the mass in an atom was contained in a small nucleus with the electrons moving around it. As electrical point charges with equal signs repel each other with a force that grows as $1/r^2$ with respect to the distance r , the concentration of positive charges in a volume as small as the nucleus ($r \sim 1-6\text{fm}$; $1\text{fm} = 10^{-15}\text{m}$) called for a new force that was stronger than the electromagnetic, at least at nuclear distances. In nuclear physics it was discovered that the strong interaction gives a nearly constant contribution to the binding energy per nucleon over a vast range of nuclei. The strong force field of a nucleon could thus only be felt by its nearest neighbors, implying that the range of the field was about the size of a nucleon.

In 1935 Yukawa developed a field theory of the nuclear force with field quanta of non-zero mass. The mass of these new particles was predicted to be of the order of 0.1 GeV from the requirement that the Compton wavelength $\hbar/mc$ equalled the range of the strong force $r_s \sim 1\text{fm}$. This particle was identified with

the spinless π -meson of mass $\sim 140 \text{ MeV}/c^2$ that was discovered in 1947. Since that an increasing number of hadrons with masses higher than the pions have been discovered, both mesons and baryons.

With the success of QED, Quantum Electro Dynamics, in the early 50's followed several attempts to use a similar field theoretical approach to describe the strong interaction. While in QED a perturbation expansion in terms of $\alpha = e^2/\hbar c \approx 1/137$ is made, the corresponding quantity for the strong interaction is $g^2/\hbar c$, which for exchange of pions is measured to be ~ 15 . Calculations of phase shifts for large l -values could nevertheless be understood as one-pion-exchange as terms for exchange of n pions will be suppressed by a factor $e^{-(nm_\pi c/\hbar)r}$ (this also rules out exchange of heavier hadrons e.g. ρ -mesons).

To avoid the problems connected with a perturbation expansion, an exploration of the analyticity properties of scattering amplitudes was made, leading to dispersion relations. These gave several predictions in the high energy limit, some successful, some not. A common problem for these was that the theory didn't gave any indication of how high the energy had to be for the relations to hold. Although dispersion relations and other methods described many features of strong interactions, they lacked the general ability of prediction that QED had for electro dynamics.

However, times were to change for the better.

3. Quarks & Gluons

In the 60's it was showed that the quantum numbers for the then known hadrons could be systematized in a scheme with simpler entities called quarks (the Eightfold Way). The baryons were build up of 3 quarks, the mesons of a quark and an antiquark. Hadron spectroscopy at the time demanded 3 different types, flavours, of quarks, called up, down and strange (u,d,s).

This success intensified the search for more elementary particles inside the hadrons. These would be easy to detect as quarks have fractional electrical charges ($u: +2/3$, $d: -1/3$). However, no isolated quarks were seen. After a period of some disbelief in the concept of quarks as particles, it was discovered in deep inelastic scattering on protons that the latter behaved as if composed of 3 particles with the quantum numbers expected for quarks. The force that "glued" the quarks together inside the hadrons had to be mediated by new elementary particles, which were called gluons. These were expected to be massless and experiment showed that they had to be vector mesons.

4. QCD

To avoid breaking the Pauli principle in spectroscopy, the concept of colour was introduced. Each quark could have an additional quantum number called colour: red, green or blue. The hadrons were "white", i.e. colour singlets.

In the 70's a gauge theory called QCD, Quantum Chromo Dynamics, was proposed for the interaction between quarks (and gluons). The charge of this interaction is colour. QCD is analogous to QED but more complicated. Apart from that there are 3 colour charges but just 1 electric charge, the basic difference is that gluons carry colour while the photon is electrically neutral (belonging to an octet, the gluons have charges of the type red-antiblue etc.). The colour charge of a quark will therefore be distributed in a "blob" around the quark. As the energy increases and smaller distances are probed in quark-quark scattering, the lesser of the charged blob will be seen by the interacting particles and consequently the strong coupling constant, α_s , will decrease. In lowest order it is given by QCD as (Q^2 = squared momentum transfer):

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda^2)} \quad (1)$$

n_f is the number of flavours available in the energy regime (at least 3), while Λ is a parameter of the order 0.1 GeV. For high energies it is therefore possible to use perturbation theory and calculate cross sections from lowest order Feynman diagrams. However, at long distances α_s becomes large and the potential energy grows linearly with the separation between the quarks. The quarks will therefore be confined inside a limited space, the bag, whose size will be about 1 fermi (confinement, the impossibility of having free quarks, has not yet been proven theoretically).

The bag acts as a "bubble" in a QCD vacuum of complicated structure, enclosing a domain of perturbative vacuum, where the quarks are located. If one tries to kick out a quark from a hadron, the outgoing quark will stretch the bag, which will exert a pressure on the quark. If the kicked out quark doesn't have enough energy it will slow down and stop, giving as a result a hadron in an excited state. However, if the energy is high the bag will continue to stretch, resulting in a colour flux tube between the quark and the remaining diquark/antiquark. Eventually it will be energetically favourable to create a quark-antiquark pair in the colour flux tube and the first quark will be contained in an outgoing meson. This process is called fragmentation. If the stretched system has enough energy left, new quark-antiquark pairs are created, giving a jet of particles going out in roughly the same direction.

In deep inelastic scattering two time scales are involved. Firstly, a short time scale, corresponding to a hard process (large momentum transfer), for the scattering of a quark against a virtual photon (or hard gluon in high- p_t hadron-hadron collisions). This process can be calculated using perturbation theory. Secondly, a long time scale, concerning the stretching of the colour flux tube and consequent fragmentation. This is a soft process (small momentum transfer) and perturbation theory can't be used. Instead one has to resort to phenomenology. Even if a complete solution of QCD was at hand (a possibility that few but the most optimistic consider as realistic in the near future), the large number of

particles in a jet would probably force one to use some phenomenological approach for a practical calculation.

5. Paper I. Production of K^+ and K^- as a Test on Models for Large p_T Hadronic Reactions.

For interactions controlled by a dimensionless coupling constant like QCD the p_T -behavior of $d\sigma/dt$ in scattering at large momentum transfer can be determined from the primary interaction by counting rules. If this primary interaction is quark-quark scattering, one expects $d\sigma/dt \sim p_T^{-4}$. Experiments at the energies available at accelerators in the late 70:s, showed $d\sigma/dt \sim p_T^{-8}$. This is what is expected from scattering of a quark against a meson (the meson comes from the "sea"). These experimental results were a drawback for the idea of hard quark scattering. However, scalebreaking effects in QCD might modify the p_T -behavior expected from scaling arguments, as the structure functions $u(x, Q^2)$, the fragmentation function $D(z, Q^2)$ and the coupling constant $\alpha(Q^2)$ all depend on Q^2 , the square of the momentum transfer. Other scalebreaking effects comes from non-vanishing primordial transverse momenta for the incoming quarks. Feynman, Field and Fox [1] have shown that this could lead to a behavior of the observed type; $Ed^3\sigma/dp^3 \sim f(x_T)/p_T^8$: at least for $p_T \leq 8$ GeV/c. This result is however model dependent and is therefore no compelling argument for QCD and hard scattering.

In paper I we show that in pp collisions at 90° large scalebreaking effects occur because of the large contribution to the inclusive cross section from scattering of low energy sea quarks at 90° . K^+ ($u\bar{s}$) can be produced as a first rank meson in the fragmentation of a valence quark (a u-quark from the proton), whereas K^- ($s\bar{u}$) cannot. Assuming the sea to be invariant under charge conjugation, jets from sea quarks will however give an equal amount of K^+ and K^- (provided the hard scattering doesn't contain flavour exchange). The same holds for gluon jets.

The difference $Ed^3\sigma/dp^3(K^+) - Ed^3\sigma/dp^3(K^-)$ (later on just referred to as " K^+-K^- ") will thus only get a contribution from valence quark jets. It can be shown that scattering of a valence quark against sea quarks or gluons is suppressed relative to scattering between two valence quarks. Scalebreaking effects are therefore expected to be much smaller for K^+-K^- than for the inclusive K^+ - and K^- -spectra. A fit of K^+-K^- to a function of the form $Ax_T(1-x_T)^m p_T^{-n}$ for pp-scattering data from ISR and FNAL with $p_T > 0.5$ GeV/c gave the result $n=5.4$, which is close to 4, the value expected from scaling. This indicates that the primary process is indeed hard scattering of valence quarks.

6. Paper II. A Model for the Reaction Mechanism and the Paryon Fragmentation Distributions in Low p_T Hadronic Interactions.

We picture a low- p_T hadronic reaction as a collision between two bags containing quarks, where two of the colour charges (distributed in "blobs" around the quarks) from the two hadrons will overlap. This will create a colour tunnel between the remnants, giving a stretched-out bubble in the vacuum. As there is no vacuum pressure behind the connected blobs, the pressure in front of these will act as an attractive force between them. When the connected blobs have lost all their energy, the vacuum pressure will act on the next one. This will continue until the original hadron energy-momentum is transferred into energy of the stretched field. The result is an essentially one-dimensional system with one quark at the endpoint (called L-quark, L for leading), one near the interaction region (I-quark, I for interaction) and, in case of a baryon, one somewhere in between (J-quark, J for junction). We assume that the stretched bag will fragment in the same manner as for quark jets. Almost all experimental data on hadron-hadron collisions comes from reactions where one of the colliding particles is a proton. For a comparison with experiments this case is therefore of particular interest. The diquark content in a proton (uud) is according to SU(6): $1/3(uu)_1 d + 1/6(ud)_1 u +$

$1/2(u\bar{d})_0 u$ (the figures indicate probabilities = amplitudes²) where the subscripts denotes spin. A low- p_T reaction is considered to occur on a relatively long timescale, making it probable that the quarks "remember" the pre-interaction diquark structure. A $(u\bar{d})_0$ is expected to be a more tightly bound system than the 1-diquarks. Considering this, we are led to the result that the d-quark will be I-quark with probability $1/3$, J-quark with $7/12$ and L-quark with $1/12$. Assuming a distribution for the J-quark as $dP/dx = 6x(1-x)$ (with the L-quark at 1) and a flat distribution behind the J-quark for the I-quark, we get longitudinal particle spectra in good agreement with data.

7. Fragmentation of a Diquark Jet in the Lund Model.

Given initial values of $W^+ = E + p_z$ for the I-, J- and L-quarks, their flavours and the spin of the J-L-diquark, the fragmentation of the system can be calculated. The first rank particle is created by cutting of a fraction z of the string behind the L-quark. The value of z is chosen according to a flat fragmentation function $f(z)dz = dz$. In most cases, 93.5% of all, a quark-antiquark pair is created, with probability of flavours weighted as $u:d:s = 1:1:0.3$ (these values are the ones accepted in e^+e^-). If the string is cut between the J- and L-quarks, a meson will result, while a cut behind the J-quark will give a baryon (the string piece with the J-quark will always form a baryon). If the cut is also behind the I-quark, if a such is present (in i.e. low- p_T pp collisions), a baryon will form, containing all the initial valence quarks.

The resulting 6.5% are cases when a diquark-antidiquark pair is created. A diquark together with a quark will of course form a baryon. We don't allow any of the pairs created nearest to the J-quark to be a diquark-antidiquark pair, as exotic states are not considered in the model. After the first rank particle is formed, the remaining string will continue to fragment in the same manner, giving a recursive scheme. A quark and antiquark created in the field is given a transverse momentum p_T of the

same size but in opposite directions. The probability function for this p_T is given by a gaussian, $e^{-(p_T/\sigma)^2}$, where the value $\sigma=0.44$ GeV/c is used.

The simple process of fragmentation of the string system described above, is however modified in two ways. The first concerns creation of baryons, where weighting factors according to SU(6) symmetry are introduced. Experiment shows that spin-1 mesons and spin-0 mesons are produced in the ratio 1:1, instead of 3:1 as is expected from simple spin counting. The former ratio is therefore also used in the model. A similar suppression of the available spin states for the decuplet baryons is expected, resulting in equal probabilities for production of spin-3/2 and spin-1/2 baryons. The other complication is of a more dynamical nature. A quark-antiquark pair can't classically be created in a single point if the particles have a transverse mass. The two particles has to be produced in two different points, in order to gain the field energy between them. They will continue in the x-t space along the branches of a hyperbola as they are accelerated by the field. The asymptotes of the hyperbola cross each other in the classical "production point". The transfer of field energy into transverse mass can be described as a tunneling phenomena. If the production point for a heavy quark-antiquark pair is very early, one expects the production to be suppressed, as the total string is very short. One also expects a suppression for production of such a pair too near the J-quark, as the field changes direction here.

8. Paper III. Hyperon Polarization and Transverse Momentum Properties in Proton Fragmentation

Assuming a string with no (or strongly suppressed) transverse excitation modes, the polarization of inclusively produced Λ -particles can be explained [2]. Conversely, the fact that a polarization exists is a support for the description of the stretched colour field as an essentially one-dimensional system.

The basic idea is simple. A Λ^0 (uds) with large x_F is most easily produced by the creation of an $s\bar{s}$ -pair in the field behind the J- and L-quarks when these together compose an $(ud)_0$ -diquark. As the $(ud)_0$ doesn't have any spin, the spin of the s-quark will also be the spin of the Λ^0 . The s and the $\bar{s}$ are produced in two points with a distance between them that is proportional to the transverse mass. As the created quarks are given equal-sized but opposite transverse momenta, an angular momentum is introduced. To compensate for this, the quarks get a polarization of the spins. This mechanism provides a polarization that increases with p_T of the observed particle.

If a baryon is described by a model in which three quarks move along the string pieces of a Y-shaped string system, the result of kicking out one of them will be an essentially linear system like the one studied in paper II. An extra feature is however present now. The J-quark will be at the end of a short string piece and the other end of this, the junction of the three strings, will move with a velocity that depends on the details concerning the way the first quark was kicked. Averaging over angles, one arrives at a velocity ~ 0.7 . This is also the velocity the J-quark will have the first time after the interaction.

The I-, J- and L-quarks are given a primordial p_T according to a gaussian probability function, with the extra requirement that their sum shall vanish. We have used $\langle k_T^2 \rangle = (0.4 \text{ GeV}/c)^2$ in our calculations.

With this extended model for low- p_T reactions polarization effects has been studied for several hyperons and a larger range of x_F -values. For Λ^0 , the dominating contribution still comes from production of an s-quark behind a $(ud)_0$ -diquark. The same polarization mechanism as before will then work. The case is similar for Σ^+ (uus) and Σ^0 (uds), but here the (uu)- and (ud)-diquarks have spin 1, resulting in a polarization in the opposite direction. Σ^- (dds) differs from Σ^+ and Σ^0 in that at least two of the quarks must come from the fragmentation of the field. In this case the d-quark polarization is more important

than the s-quark polarization, as the former will determine the spin of the $(dd)_1$ -diquark. In order to produce a Ξ^- (dss) or a Ξ^0 (uss) containing the J-quark, an s-quark has to be produced both in front of the J-quark and behind it. If these have p_T in the same direction, they will be polarized in opposite directions. One would therefore not expect any net Ξ -polarization. However, as the J-quark is moving with a velocity ~ 0.7 it is much harder to produce an s-quark with a high p_T in front of the J-quark than behind it. The p_T -spectra for the two s-quarks will both approximately be gaussian i.e. $dN/dp_T^2 \sim e^{-bp_T^2}$, but the slope b will be much smaller for the quark behind the J-quark. Thus a polarization in the same direction as for Λ^0 results.

Paper IV. Fragmentation Structure in High- p_T Events

High- p_T events in hadron-hadron collisions are of great interest, as these are expected to be the result of an initial hard scattering between two "partons" (quarks or gluons) in the colliding particles. The cross section for this primary process can be calculated using perturbative QCD. A direct comparison between theory and experimental data is unfortunately impossible as one can't observe the scattered partons alone, but just the result of the fragmentation of the colour field between parton and remnant. The Lund model describes this last soft process in a consistent way. In this model quarks are located at the endpoints of a massless relativistic string, while gluons are considered as kinklike excitations of the string. A Monte Carlo program for simulation of quark and gluon jets exists [3] and in order to be able to use this to simulate high- p_T events, a study of the lowest order calculations in perturbative QCD has been made.

When gluons are involved, it is necessary to know the precise way the string is stretched, as this is important for the fragmentation. These different topologies of the final state are associated with different colour factors in the production amplitudes [4]. Using this one can calculate the amplitude corresponding to a specific string configuration. Amplitudes for different string topologies will in general not be

orthogonal. As the interference terms are suppressed by a factor $1/N^2$ (N = number of colours) compared to the other terms we find it permissible to discard them. It is possible that these different string configurations corresponds to topological quantum numbers. In that case one expects the interference terms to vanish.

A Monte Carlo program has been developed for high- p_T physics. The program includes structure functions and can be used to simulate complete high- p_T events.

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